Applied Thermal Engineering 63 (2014) 354–361

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Comparative analysis between a PEM fuel cell and an internal combustion engine driving an electricity generator: Technical, economical and ecological aspects

Lúcia Bollini Braga*[,1], Jose Luz Silveira [1], Marcio Evaristo da Silva [1], Einara Blanco Machin [1], Daniel Travieso Pedroso [1], Celso Eduardo Tuna [1]

Sao Paulo State University (UNESP), Guaratinguetá 12516-410, SP, Brazil

HIGHLIGHTS

- The exergetic efficiency of ICE-G was 22% and for the fuel cell was 40%.
- The PEM fuel cell at long-term become economically competitive compared to ICE-G.
- The ecological efficiency of PEM fuel cell was 96% and Diesel ICE-G was 51%.

ARTICLE INFO

Article history:
Received 25 June 2013
Accepted 28 October 2013
Available online 7 November 2013

Keywords:
Economic analysis
Ecological analysis
Technical analysis
Internal combustion engine
Proton exchange membrane fuel cell

ABSTRACT

In the recent years the fuel cells have received much attention. Among various technologies, the Proton Exchange Membrane Fuel Cell (PEMFC) is currently the most appropriate and is used in several vehicles prototype. A comparative technical, economical and ecological analysis between an Internal Combustion Engine fueled with Diesel driving an electricity Generator (ICE-G) and a PEMFC fed by hydrogen produced by ethanol steam reforming was performed. The technical analysis showed the advantages of the PEMFC in comparison to the ICE-G based in energetic and exergetic aspects. The economic analysis shows that fuel cells are not economic competitive when compared to internal combustion engine driving an electricity generator with the same generation capacity; it will only be economically feasible in a long term; due to the large investments required. The environmental analysis was based on concepts of CO_2 equivalent, pollution indicator and ecological efficiency. Different to the ICE-G system, the Fuel Cell does not emit pollutants directly and the emission related to this technology is linked mainly with hydrogen production. The ecological efficiency of PEMFC was 96% considering the carbon dioxide cycle, for ICE-G system this parameter reach 51%.

1. Introduction

The criteria that influence the evolution of the world's energy sector in the present century are complex. Typical objectives are safety in supply and exploitation of resources, competitiveness of companies and the necessity to preserve the environment (locally and globally) through the use of new technologies and the sustainable use of existing resources [1,2].

In the energy field, the main worldwide preoccupation is focused on environmental problems. Recently, the pollutant indicators reduction of toxic substances in the environment, produced by the industrial and the automotive transportation sectors, is one of the most important targets that are being taken into account in the majority of the industrialized countries. Both sectors must adopt future strategies for the reduction of pollutant emission into the atmosphere, with the purpose of reducing the hazardous concentrations in the air [3,4].

One factor that influences the feasibility analysis to apply technologies that use alternative fuels is the environmental impact that such technology could cause. Many researchers have devoted themselves to decrease the emission of pollutant materials by these

* Corresponding author. Energy Department, Av. Dr. Ariberto Pereira da Cunha, 333, Pedregulho, Guaratinguetá 12516-410, São Paulo, Brazil. Tel.: +55 12 31232239; fax: +55 12 31232835.

E-mail addresses: lucia@feg.unesp.br, luciabbraga@gmail.com (L.B. Braga), joseluz@feg.unesp.br (J.L. Silveira), mevaristo@feg.unesp.br (M. Evaristo da Silva), einara@feg.unesp.br (E.B. Machin), danieltravieso@feg.unesp.br (D.T. Pedroso), celso.tuna@feg.unesp.br (C.E. Tuna).

[1] Energy Systems Optimization Group (www.feg.unesp.br/gose).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.10.053

Nomenclature

C	carbon (chemical element) "(−)"
Ct	cost (US$/kWh)
C_2H_5OH	ethanol "(−)"
$C_{12}H_{26}$	Diesel "(−)"
CO_2	carbon dioxide "(−)"
$(CO_2)_e$	equivalent carbon dioxide (kg/kg_{fuel})
Cp	specific heat at constant pressure (kJ/kg K)
E	power (kW)
e_n^{-CH}	standard chemical exergy (kJ/kmol)
e^{-CH}	standard chemical exergy (kJ/kg)
EtOH	ethanol "(−)"
Ex	exergy (kW)
Ex	specific exergy (kJ/kg)
f	annuity factor (1/year).
FC	Fuel Cell "(−)"
H	hydrogen (chemical element) "(−)"
Hp	equivalent period of operation (h/year)
h	specific enthalpy (kJ/kg)
H_2O	water "(−)"
I	irreversibility flow rate (kW)
ICE	Internal Combustion Engine "(−)"
ICE-G	Internal Combustion Engine Generator "(−)"
i	investment cost (US$/kW)
k	payback period (year)
LHV	Lower Heating Value (kJ/kg)
M_{CO2}	carbon dioxide emission ($kgCO_2/kg_{fue}l$)
$\dot{m}$	mass flow (kg/s)
n	molar mass of fuel (kg/kg_{mol})
N	nitrogen (chemical element) "(−)"
N_2	nitrogen "(−)"
NO_x	nitrogen oxide "(−)"
O	oxygen (chemical element) "(−)"
O_2	oxygen "(−)"
P	pressure (atm)
PEMFC	Proton Exchange Membrane Fuel Cell "(−)"
PM	particulate matter "(−)"
R	universal gas constant (kJ/kmol K)
r	annual interest rate (%)
s	specific entropy (kJ/kg K)
S	sulfur (chemical element) "(−)"
SO_2	sulfur dioxide "(−)"
T	temperature (°C)
V	voltage (Volt)
X_n	mole fraction "(−)"
W	power output (kW)

Subscripts

ch	chemical "(−)"
E	output "(−)"
el	electricity "(−)"
elc	electric "(−)"
I	input "(−)"
main	maintenance "(−)"
0	reference state "(−)"
P	generated "(−)"
S	supplied "(−)"
tm	thermodynamic "(−)"

Greek letters

α	air excess (%)
η	electric efficiency (%)
λ	air stoichiometrical coefficient "(−)"
φ	factor rate between standard chemical exergy and lower heating value "(−)"
ψ	exergetic efficiency (%)
π_g	pollutant indicator (kg/MJ)
ε	ecological efficiency (%)

technologies, trying to reverse the current environmental situation. The control of emission substances, such as: particulate matter (PM), CO_2, SO_2, and NO_x represents a major concern all over the world [5,6].

Brazil has developed many sustainable energy programs in order to reduce carbonic gas emission. Those programs use technologies that not only are respectful to the environment but also techno-economically competitive; for instance: hydrogen production, biodiesel production, ethanol production, and producer gas generation from biomass gasification, especially micro-scale system gasifiers, associated to an internal combustion engine. Some of these fuels could be used directly in conventional combustion systems; however, others need some kind of conditioning to replace the conventional fuels [6].

Among several technologies nowadays, Fuel Cell (FC) appears as a promising alternative for electricity generation, principally in substitution of the Internal Combustion Engine fueled with Diesel driving an electricity Generator (ICE-G) [7,8]. The FC is a very efficient system that converts the chemical energy from a fuel into electricity through a chemical reaction rather than combustion. As residual of the process water, electricity, and heat are generated through the combination of hydrogen and oxygen in the FC [7].

There are some researches considering several aspects of the fuel cells and internal combustion engines behavior. Barelli et al. [8], developed a study in combined heat power systems based on a (PEMFC), Rakopoulos et al. [9] performed research about energy and exergy analysis of an ICE and Zamel et al. [10] published a full analysis of the impact of the difference between the Canadian and American energy realities on the lifecycle of fuel cell vehicles and internal combustion engine vehicles. The PEMFC could substitute the ICE in several kinds of situations, such as: in the transport sector, in the stationary or distributed generation, among others; however there are not papers published in the literature with a comprehensive comparison of technical, economical and ecological aspects between both systems, to help decision makers choose which is in fact, the best device for a specific application.

On this background, the goal of this paper is to perform the comparative analysis between the PEMFC and the ICE-G based on the technical, economical and ecological aspects. Firstly, it was performed the technical analysis, based on the exergetic efficiency, in order to have the true efficiency of both systems. Afterward, an economical analysis was realized in order to have the economic feasibility of the implementation of both systems; finally was performed an ecological analysis based on concepts of equivalent carbon dioxide, pollutant indicator, and ecological efficiency.

2. Methodology

2.1. Systems description

In the present work, it was analyzed an ICE-G and a PEMFC, both systems with a generation capacity of 5 kW of electricity; the heat produced by both systems was despised.

Figs. 1 and 2 shown a representation of the physical configuration of the ICE-G and the PEMFC systems respectively, indicating all the flows, as well as the operation parameters (temperature, pressure, etc.).

For the thermodynamic analysis of the ICE-G, the Eqs. (1) and (2) were applied as follows:

$$\eta_{elc} = \frac{E_p}{E_{S_{fuel}}} \tag{1}$$

$$E_{S_{fuel}} = \dot{m}_{diesel} \times LHV_{diesel} \tag{2}$$

where:

$E_p = 5$ kW

$\eta_e = 0.27$ [11] (considering a thermal efficiency equal to 0.30 and the electricity generator efficiency equal to 0.9)

$LHV_{diesel} = 42,490$ kJ/kg [7]

Through these values, was determinate the mass flow rate ($\dot{m}_{diesel}$) of Diesel equals to 0.000436 kg/s, and through Eq. (3) (stoichiometric equation of Diesel combustion), considering 100% of air excess (α), was possible to calculate the mass flow rate of inlet air and the mass flow rate of exhaust gases.

$$1C_{12}H_{26} + 18.5\alpha O_2 + 69.56\alpha N_2 \rightarrow 12CO_2 + 13H_2O + 69.56\alpha N_2 + 18.5(\alpha - 1)O_2 \tag{3}$$

In order to calculate the inlet and outlet streams of the PEMFC, the Equations (4)–(7), were considered according to Larminie and Dick [12]:

$$\dot{m}_{air,reactant} = 3.57 \times 10^{-7}\left(\frac{\lambda W}{V}\right) \tag{4}$$

$$\dot{m}_{H_2,reactant} = 1.05 \times 10^{-8}\left(\frac{W}{V}\right) \tag{5}$$

$$\dot{m}_{air,product} = 3.57 \times 10^{-7}\left(\frac{\lambda W}{V}\right) - 8.29 \times 10^{-8}\left(\frac{W}{V}\right) \tag{6}$$

$$\dot{m}_{H_2,product} = 9.34 \times 10^{8}\left(\frac{W}{V}\right) \tag{7}$$

Where:

$W = 5$ kW
$V = 0.5$ V [13]
$\lambda = 3$

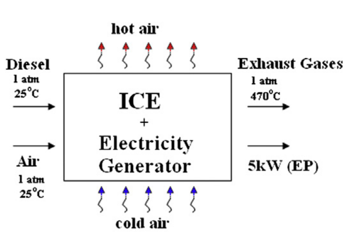

Fig. 1. Internal Combustion Engine fueled with Diesel driving an electricity Generator (ICE-G).

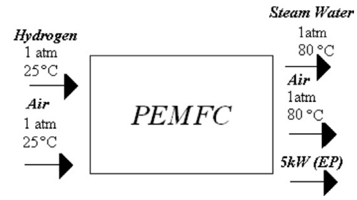

Fig. 2. Proton Exchange Membrane Fuel Cell (PEMFC).

The equations to calculate the mass flow rate of the products and the reactants in the fuel cell (Eqs. (4)–(7)) dependent on the power output (W), on the fuel cell voltage (V) and on the stoichiometric air coefficient (λ). The mass flow of one product, the air, can be defined as the difference between the amount of oxygen that enters into the PEMFC and the oxygen that is consumed by the reaction with hydrogen to produce water. The efficiency of the fuel cell can be greatly improved if λ is increased; however is recommended that the λ value ranges between 2 and 4, in order to maintain the relative humidity level in the product air to avoid drying of the fuel cell membrane at the high operating temperatures [13].

2.2. Exergetic balance

An important tool to evaluate the performance of the thermal system is the exergetic balance. This analytical procedure is very similar to the energy balance. The energy balance is based on the First Law of thermodynamics (energy conservation), whilst the exergetic balance is based on the Second Law of thermodynamics. The exergetic balance is performed considering that the energy degradation being equivalent to the energy loss, due to the fact that real processes are irreversible [14].

According to Nogueira et al. [15], the exergetic calculation is mainly determined by the thermodynamic balance, by the difference between the concentration of chemical species, by chemical potential associated to the reactions and also by other factors with minimal contributions.

In this way, exergy can be defined as the maximum obtainable work from a given form of energy, using environmental parameters as the reference state. One of the main uses of this concept is in the exergy balance, which may be analyzed as a measure of the energy degradation. In the absence of magnetic, electrical and nuclear effects, the exergy of a system, if the changes in kinetic and the potential exergies are neglected, is given by Eq. (8) [16].

$$ex = ex_{TM} + ex_{CH} \tag{8}$$

where the first term represents the portion of exergy associated to heat transfer on the control surface. In this work, is important that the air and the gases are considered ideal gases; in that case the first term of Eq. (8) can be evaluated through Eq. (9), which considers constant Cp (specify heat at constant pressure) [16], and when they cannot be considered as ideal gases like the water vapor produced by a PEMFC, the Eq. (10) is used [6].

$$ex_{TM} = \int_{T_0}^{T} Cp\left[1 - \left(\frac{T_0}{T}\right)\right] dT + RT_0 \ln\left(\frac{P}{P_0}\right) \tag{9}$$

$$ex_{TM} = (h - h_o) - T_o(s - s_o) \tag{10}$$

To calculate the second term of Eq. (8), that represents the portion of chemical exergy, is used the Eq. (11) [13], unless in the case of Diesel fuel, where is used the Eqs. (12) and (13) [6].

$$ex_{CH} = \sum x_n e_n^{-CH} + RT_0 \sum x_n \ln(x_n) \quad (11)$$

$$\phi = 1.0401 + 0.1728\frac{H}{C} + 0.0432\frac{O}{C} + 0.2169\left(1 - 2.0628\frac{H}{C}\right) \quad (12)$$

$$\phi = \frac{ex^{-CH}}{LHV} \quad (13)$$

Finally, the total exergy of the system is shown in Eq. (14) [16].

$$Ex = \dot{m}(ex_{TM} + ex_{CH}) \quad (14)$$

The temperature and the pressure of the environment were set equal to the reference values, 25 °C and 1 atm respectively. The atmosphere was modeled as an ideal-gas mixture with the composition shown in Table 1 [8].

The efficiencies (mechanical, thermal, etc.) are not traditionally based on the Second Law of thermodynamics. Recent developments of the exergetic analysis allow the definition of new performance criteria, offering advantages over the traditional criterions. According to Kotas [17], the rational efficiency, shown in Eq. (15), is based on the following scheme:

$$I = Ex_i - Ex_E \geq 0 \quad 1 - \frac{Ex_E}{Ex_i} \geq 0 \quad \psi = \frac{Ex_E}{Ex_i} < 1 \quad (15)$$

3. Economical analysis

This section economically compares the electricity cost produced by the PEMFC and the ICE-G systems. The PEMFC in this work is fueled with hydrogen produced by the sugar cane ethanol steam reforming and the ICE is fueled with Diesel. For the calculation of the electricity cost (Ct_{el}) generated by the PEMFC system, the following considerations were used: the cost of hydrogen production by the ethanol steam reforming was considered 0.09 US$/kWh [18]. The investment cost in a PEMFC will probably decrease in some years. With the technological evolution and the increase of production units, the cost of a PEMFC ranges between 1000 US$/kW and 5000 US$/kW [19]; according to that in this paper three different values of investment (i_{FC}) were considered for this technology, which are: 1000 US$/kW, 2500 US$/kW and 5000 US$/kW.

Other parameters that were considered for the calculus in the PEMFC system are: $W = 5$ kW (electric power); LHV (hydrogen) = 119,742.48 kJ/kg [7]; Hp = 6570 h/year (18 h/day, during 1 year).

For the calculation of the electricity cost (Ct_{el}) using the ICE-G system, the following considerations were used: the cost of Diesel was 0.06 US$/kWh [20]; the investment cost in an ICE-G (i_{ice}) was considered 500 US$/kW [20–22]. Other parameters that were considered for ICE-G system are: $W = 5$ kW (electric power); LHV (Diesel) = 42,490 kJ/kg [7] and Hp = 6570 h/year.

The Equations (16) and (20) [23] were used for the calculation of the cost of the electricity generated in both systems.

Table 1
Mole Fractions and chemical exergy (kJ/kmol) of reference components in the atmospheric air [8].

Component	Mole Fraction, x_n	Chemical exergy, e_n^{-CH} (kJ/kmol)
N_2	0.79	720
O_2	0.21	3.970

$$\dot{m} = \frac{W}{\eta \times LHV} \times 100 \quad (16)$$

$$q = 1 + \frac{r}{100} \quad (17)$$

$$f = \frac{q^k(q-1)}{q^k - 1} \quad (18)$$

The global equation for the electricity cost was considered as Eq. (19) [23].

$$Ct_{el} = \left(\frac{i_{system} \times f}{Hp}\right) + \left(\frac{Ct_{fuel} \times LHV \times \dot{m}}{W}\right) + Ct_{main} \quad (19)$$

where the maintenance cost (Ct_{main}) was considered as 3% of investment cost and is shown in Eq. (20).

$$Ct_{main} = 0.03 \times \left(\frac{i_{system} \times f}{Hp}\right) \quad (20)$$

4. Ecological analysis

In order to make possible to compare the ecological efficiency between an ICE-G and a PEMFC, was necessary to calculate the ecological efficiency of hydrogen production that feeds the fuel cell, due to the only products of a PEMFC are steam and electricity. The PEMFC cannot be considered a pollutant system, but the hydrogen that feeds it is not found already isolated in nature, so it must be produced and consequently it consumes energy and emits pollutants. In this paper, the hydrogen that feeds the PEMFC was produced by an ethanol steam reforming, and the energy consumed during the hydrogen production was obtained from sugar cane bagasse. In the case of the ICE-G, was necessary to take into account the emissions to produce the Diesel fuel in the refinery (Diesel from petroleum). Moreover, was necessary to consider the emission when consumed by ICE-G (combustion process). The emissions in the combustion process of Diesel in an internal combustion engine are based on the value reported by Taylor [24].

4.1. The equivalent carbon dioxide and pollutant indicator

The equivalent carbon dioxide $(CO_2)_e$ is composed by a hypothetical pollutant concentration factor that can be determined by the Equation (21). For the calculation of this coefficient, the maximum value for the CO_2 concentration is divided by the corresponding air quality standard for NO_x, SO_2 and PM in 1 h [6].

$$(CO_2)_e = CO_2 + 80\,SO_2 + 50\,NO_x + 67PM \quad (21)$$

The best fuel from the ecological standpoint is the one which presents a minimum amount of $(CO_2)_e$. In order to quantify this environmental impact, the pollutant indicator (π_g) is defined by Eq. (22) [6].

$$\pi_g = \frac{(CO_2)_e}{LHV} \quad (22)$$

where $(CO_2)_e$ is taken in kg per kg of fuel (kg/kg), the LHV of the fuel is expressed in MJ/kg, and π_g is expressed in kg/MJ.

4.2. Ecological efficiency

The ecological efficiency is defined as an indicator which allows the evaluation of the systems performance, according to pollutants

emissions, by comparing the hypothetically integrated pollutants emissions (CO_2 equivalent emissions) with the existing air quality standards. The conversion efficiency is also considered as a determining factor on the specific emissions, expressed by a number. Eq. (23) can be used for determining the ecological efficiency [6]:

$$\varepsilon = \left[\frac{0.204 \times \eta_{\mathrm{system}} \times \ln(135 - \pi_g)}{\eta_{\mathrm{system}} + \Pi_g}\right]^{0.5} \quad (23)$$

where "ε" comprises in a single coefficient, the aspects that define the environmental impact intensity; and ranges between 0 and 1. The situation that is considered unsatisfactory from the ecological point of view is when $\varepsilon = 0$; however, $\varepsilon = 1$ indicates an ideal situation from the ecological efficiency point of view [6].

4.3. Calculation methodology of the ecological efficiency

The ecological efficiency of a PEM fuel cell considered the pollutants emission of the hydrogen production by the ethanol steam reforming; it was based on Fig. 3.

For the purpose of calculate the ecological efficiency of a Diesel ICE-G, was considered the ecological efficiency factor of Diesel production in the refinery and the combustion process in an ICE-G, as shown in Fig. 4.

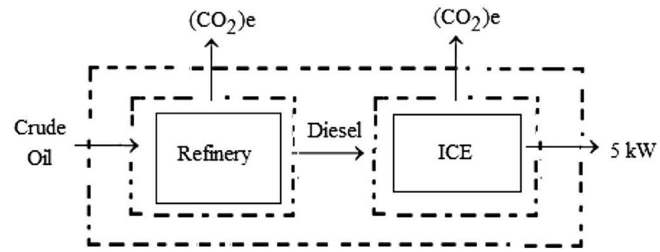

Fig. 4. Electricity production by an ICE-G, considering the emissions in a refinery and in the combustion process.

Table 2 shows the elementary composition of sugar cane bagasse in a dry base, from which was determined the stoichiometric equation of bagasse combustion process shown in Equation (24). In this case, as there is not chemical formula defined for this kind of fuel, it was made the equation of combustion for 100 g of fuel (sugar cane bagasse) with 30% of air excess [25].

$$a_1\mathrm{C} + b_1\mathrm{H} + c_1\mathrm{O} + d_1\mathrm{N} + e_1\mathrm{S} + 3.83(\alpha \mathrm{O_2} + \alpha \mathrm{N_2}) \rightarrow w_1\mathrm{CO_2} + y_1\mathrm{H_2O} + 3.83\alpha(1-\alpha)\mathrm{O_2} + 3.83\alpha \mathrm{N_2} \quad (24)$$

where:$\alpha = 1.30$ (considering 30% of air excess in the bagasse combustion);a_1; b_1; c_1; d_1; e_1; w_1; y_1 – are the values of elementary components of bagasse, determined by the ratio between the elementary composition and the molar mass of the according element.

4.3.1. Calculation of carbon dioxide emissions in the combustion process of sugar cane bagasse

According to Villela et al. [27], the carbon dioxide emission result of the combustion of 1 kg of fuel, can be calculated using the Equation (25), as follows:

$$M_{CO_2} = \frac{(w_1 44.1)\mathrm{CO_2}}{n} \quad (25)$$

The molar mass of bagasse can be determined according to the elementary composition and the stoichiometric equation (Table 2 and Equation (24)). In this way, the molar mass of sugar cane bagasse can be calculated through Equation (26):

$$n = (a_1 1.12) + (b_1 1.1) + (c_1 1.16) + (d_1 1.14) + (e_1 1.32) \quad (26)$$

4.3.2. Emission of ethanol steam reforming system

The emission values of NO_x, SO_2 and PM of the bagasse combustion process are reported by Lora et al. [25], and are shown in Table 3.

Using the stoichiometric reaction of sugar cane bagasse combustion (Eq. (24)), the global stoichiometric reaction of ethanol steam reforming (Eq. (27)) and the carbon dioxide lifecycle from sugar cane plantation to ethanol production, shown in Fig. 5, it was possible to obtain the emission of the ethanol steam reforming processes. For this calculation, it was considered the following ratio (1 ton of sugar cane produces 83.33 L of ethanol and 250 kg of bagasse) [28]

$$\mathrm{C_2H_5OH} + 3\mathrm{H_2O} \rightarrow 2\mathrm{CO_2} + 6\mathrm{H_2} \quad (27)$$

4.3.3. Emission of Diesel

The emissions values of Diesel production in a refinery and in combustion process were based on the values reported by Ball et al. [29] and Taylor [24] respectively, and are shown in Table 7.

5. Results

5.1. Exergetic analysis

The results of exergetic analysis for the ICE-G and the PEMFC are showed in Tables 4 and 5, respectively.

One of the major advantages of the PEMFC is that it can attain high efficiency, since it is not limited by the Carnot cycle. On average, the electric efficiency of the PEMFC is about 20%–30%

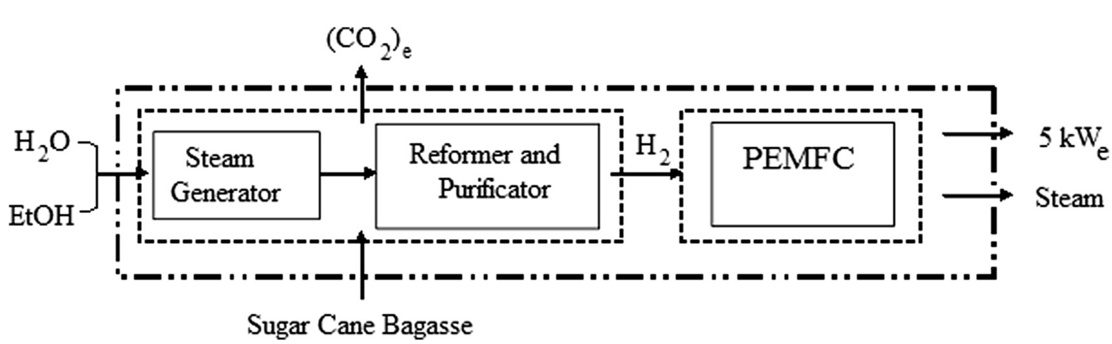

Fig. 3. Electricity production by a PEMFC using hydrogen from ethanol steam reforming.

Table 2
Characteristics of sugar cane bagasse (dry based) [26].

Biomass	Elementary composition (%)						LHV (MJ/kg)
	C	H	O	N	S	Ash	
Bagasse	44.8	5.35	39.55	0.38	0.01	9.79	17.32

Table 3
SO_2, NO_x, PM emissions of bagasse combustion [25].

Components	Combustion of sugar cane bagasse
SO_2 ($kgSO_2$/kgfuel)	0
NO_x ($kgNO_x$/kgfuel)	0.0012
PM (kgPM/kgfuel)	0.0071

higher than the combustion of fossil fuels such as Diesel, natural gas and coal [30], due to the fuel cells is based on an electrochemistry reaction.

Theoretically, the efficiency of a PEMFC and an ICE-G based on the First Law of thermodynamics makes no reference to the best possible performance of both systems, and thus, could be misleading [13]. On the other hand, the Second Law could give a true demonstration of efficiency of the system's performance.

According to the exergetic study shown in Tables 4 and 5, it can be noted that the PEMFC system attain a higher value of exergetic efficiency compared to an ICE-G system, 40.34% versus 22.36% respectively. The irreversibility of the ICE-G was 13.32 kW, while the PEMFC was 6.64 kW. That means that, for both devices producing the same power, the electricity is generated in the fuel cell with less exergetic losses (irreversibility); that's means that the PEMFC system produces more useful work than the ICE-G.

5.2. Economic analysis

The results of the economic analysis are showed in Fig. 6. The investment cost of the fuel cell ranges from 1000 US$/kW up to 5000 US$/kW [19]. The investment cost in ICE was 500 US$/kW [20].

It is possible to observe in Fig. 6, that with both systems operating 6570 h/year, the electricity cost of the ICE-G is more economically feasible than when use the PEMFC for a period up to 10 years, due to the high initial investment of the PEMFC and the higher cost of hydrogen fuel. The electricity price of PEMFC with the investment of 1,000 US$/kW, from the second years, is near to the price of the electricity produced with ICE-G (difference of 12.9%), and decrease constantly until reach a difference of 4.16% in ten years. The difference between the electricity production costs will decrease more rapidly when some barriers are broken and begin the PEMFC production at large scale; at that point this technology will become more available and reliable.

5.3. Ecological analysis

Table 6 shows the emission values calculated by hydrogen production of ethanol steam reforming. In these calculations, two scenarios were considered (one without considering the carbon dioxide lifecycle and the other taking the carbon dioxide cycle into account).

Table 4
Exergetic analysis of the ICE-G.

$ex_{TM\ diesel}$ (kJ/kg)	0
$ex_{CH\ diesel}$ (kJ/kg)	51,303.09
$Ex_{\ diesel}$ (kW)	22.35
$ex_{TM\ air}$ (kJ/kg)	0
$ex_{CH\ air}$ (kJ/kg)	0
$ex_{TM\ exhaust\ gases}$ (kJ/kg)	235.09
$ex_{CH\ exhaust\ gases}$ (kJ/kg)	27.49
$Ex_{exhaust\ gases}$ (kW)	3.53
I (kW)	13.82
ψ (%)	22.36

Table 5
Exergetic analysis of the PEMFC.

$ex_{TM\ hydrogen}$ (kJ/kg)	0
$ex_{CH\ hydrogen}$ (kJ/kg)	118.05
$Ex_{\ hydrogen}$ (kW)	12.40
$ex_{TM\ air/reactant}$ (kJ/kg)	0
$ex_{CH\ air/reactant}$ (kJ/kg)	0
$ex_{TM\ air/product}$ (kJ/kg)	4.54
$ex_{CH\ air/product}$ (kJ/kg)	4.50
$Ex_{\ air/product}$ (kW)	0.08
$ex_{TM\ water\ vapor/product}$ (kJ/kg)	198.76
$ex_{CH\ water\ vapor/product}$ (kJ/kg)	527.78
$Ex_{\ water\ vapor/product}$ (kW)	0.67
I (kW)	6.64
ψ (%)	40.34

Table 7 shows the emission values of process of Diesel production in a refinery and during in its combustion process.

Using the emissions values of CO_2, NO_x, SO_2, PM and the LVH of sugar cane bagasse equals 17.32 MJ/kg. It was determined the equivalent carbon dioxide ($(CO_2)_e$) and the pollutant indicator (π_g) of the hydrogen production system, and they were compared with the total emission of equivalent carbon dioxide ($(CO_2)_e$) of Diesel ($(CO_2)_e$ from refinery + $(CO_2)_e$ from combustion process) and the pollutant indicator (π_g), considering the LHV of crude oil equal to 42.8 MJ/kg [31]. These values are shown in Table 8.

Analyzing the hydrogen production processes by ethanol steam reforming, it was determined the thermodynamic efficiency equation of the ethanol steam reforming system ($\eta_{EtOH\ steam\ reforming}$), as shown in Equation (28):

$$\eta_{EtOH\ steam\ reforming} = \frac{E_{S_{hydrogen}}}{\left(E_{S_{bagasse}} + E_{S_{ethanol}}\right)} \tag{28}$$

where:

$$E_{S_{hydrogen}} = \dot{m}_{hydrogen} \times LHV_{hydrogen}$$

$$E_{S_{bagasse}} = \dot{m}_{bagasse} \times LHV_{bagasse}$$

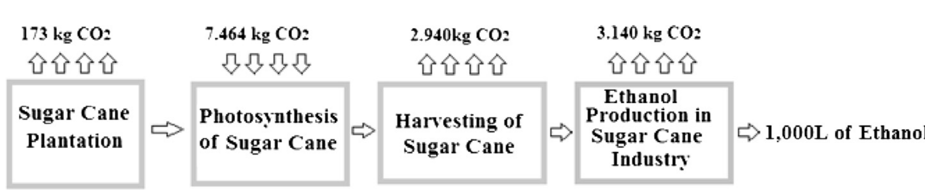

Fig. 5. Total carbon dioxide emission for 1000 L of Brazilian ethanol [7].

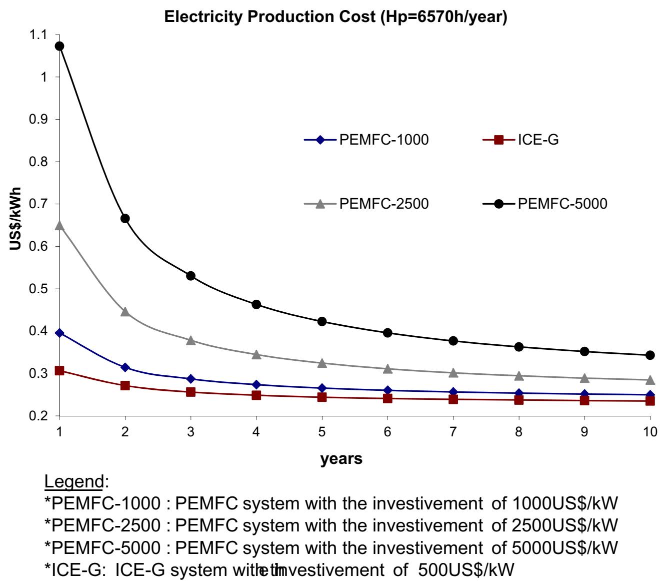

Fig. 6. Electricity production cost (US$/kWh) of the PEMFC and the ICE-G operating 6570 h/year.

$$E_{S_{\text{ethanol}}} = \dot{m}_{\text{ethanol}} \times \text{LHV}_{\text{ethanol}}$$

$$\text{LHV}_{\text{hydrogen}} = 119.95 \text{ MJ/kg}$$

$$\text{LHV}_{\text{ethanol}} = 28.3 \text{ MJ/kg}$$

$$\text{LHV}_{\text{bagasse}} = 17.32 \text{ MJ/kg}$$

Table 9 shows the results of the global thermodynamic efficiency and the ecological efficiency of electricity production of both systems. The global thermodynamic efficiency of the fuel cell system was calculated by the product of hydrogen production efficiency (55.6%) times the energetic efficiency of PEMFC device (47%) [32], and for the Diesel engine was calculated by the product of the Diesel production efficiency (31%) times the ICE-G system energetic efficiency (27%) [33,19].

Table 6
Results – emissions from the hydrogen producing by steam reforming of ethanol process.

Components	Combustion of sugar cane bagasse		Ethanol steam reforming	
	Without CO_2 lifecycle	With CO_2 lifecycle	Without CO_2 lifecycle	With CO_2 lifecycle
CO_2 ($kgCO_2$/kgfuel)	1.82389	0.46956	1.91	0.36
SO_2 ($kgSO_2$/kgCfuel)	0 [25]		0	
NO_x ($kgNO_x$/kgfuel)	0.0012 [25]		0	
PM (kgPM/kgfuel)	0.0071 [25]		0	

Table 7
Results – equivalent carbon dioxide of Diesel production and combustion process emissions.

Emission	Refinery process	Combustion process
$(CO_2)_e$	1.32 (kg/kg_{fuel}) [29]	8.529 ((kg/kg_{fuel}) [24]

Table 8
Results – equivalent carbon dioxide and pollutant indicators for the proposed system.

System	$(CO_2)_e$ (kg/kg_{fuel})		π_g (kg/MJ)	
	Without lifecycle	With lifecycle	Without lifecycle	With lifecycle
PEMFC	3.74	1.78	0.067	0.012
Diesel ICE-G	9.849		0.2307	

Table 9
Thermodynamic and ecological efficiency of electricity production of both systems.

System	η_{system} (%)	ε (%)	
		Without cycle	With cycle
PEMFC	26	63	96
Diesel ICE-G	8.37	51	

6. Conclusions

This paper shows that the fuel cell could be a promising alternative for electricity generation due to the high efficiency and the lower emission of pollutants in comparison with ICE-G. From the exergetic point of view, the comparison shows that the fuel cell system can be more efficient than the ICE-G. The ICE-G using Diesel as fuel has exergetic efficiency of 22.36%, and fuel cells have exergetic efficiency of 40.34%.

As was showed in this economic analysis, at present time, the fuel cell technology with an investment cost ranging between 1000 US$/kW and 5000 US$/kW is not economically feasible but, in a long-term, the fuel cells will become more competitive compared to the internal combustion engine fueled with Diesel driving an electricity generator. Bringing down some barriers and starting a market with a sufficient scale, justifying the investments by a further fuel cell production, and in the scaling-up of production, which will take this technology into acceptable levels of cost, availability and reliability.

Finally, according to the ecological analysis, the PEMFC using hydrogen produced by an ethanol steam reforming, is an environmentally promising technology, due to its high ecological efficiency when considering the carbon dioxide cycle, $\varepsilon = 96\%$.

The hydrogen, the main energy carrier to fuel cells and its production by the ethanol steam reforming, is the best way to guarantee the volume of production necessary to produce hydrogen in sustainable way in larger sugar cane production countries like Brazil. The integration or association of hydrogen production with the sugar industry can certainly put Brazil in a good classification in the “Hydrogen Era” in the near future.

Acknowledgements

This work is financed by FAPESP (São Paulo Research Foundation).

References

[1] A.M. Omer, Energy, environment and sustainable development, Renew. Sustain. Energy Rev. 12 (2008) 2265–2300.
[2] Z. Williamsona, D. Kimb, D.K. Chuna, T. Leea, C. Squibb, Experimental evaluation of cell temperature effects on miniature, air-breathing PEM fuel cells, Appl. Therm. Eng. 31 (2011) 3761–3767.
[3] R. Royoa, M.A.A. Arranz, J.A.C. Cubas, J. Payáa, Thermographic study of the preheating plugs in diesel engines, Appl. Therm. Eng. 37 (2012) 412–419.
[4] V. Arteconi, C. Brandoni, D. Evangelista, F. Polonara, Life-cycle greenhouse gas analysis of LNG as a heavy vehicle fuel in Europe, Appl. Energy 87 (2010) 2005–2013.

[5] O. Arpaa, R. Yumrutas, O. Kaska, Desulfurization of diesel-like fuel produced from waste lubrication oil and its utilization on engine performance and exhaust emission, Appl. Therm. Eng. 58 (2013) 374–381.
[6] R.A.M. Boloy, J.L. Silveira, C.E. Tuna, C.R. Coronado, J.S. Antunes, Ecological impacts from syngas burning in internal combustion engine: technical and economic aspects, Renew. Sustain. Energy Rev. 15 (2001) 5194–5201.
[7] J.L. Silveira, L.B. Braga, A.C.C. Souza, J.S. Antunes, R. Zanzi, The benefits of ethanol use for hydrogen production in urban transportation, Renew. Sustain. Energy Rev. 13 (2009) 2525–2534.
[8] L. Barelli, G. Bidini, F. Gallorini, A. Ottaviano, An energetic–exergetic analysis of a residential CHP system based on PEM fuel cell, Appl. Energy 88 (2011) 4334–4342.
[9] C.D. Rakopoulos, E.G. Giakoumis, Second-law analyses applied to internal combustion engines operation, Prog. Energy Combust. 32 (2006) 2–47.
[10] N. Zamel, X. Li, Life cycle comparison of fuel cell vehicles and internal combustion engine vehicles for Canada and the United States, J. Power Sources 162 (2006) 1241–1253.
[11] K.T. Yuna, H. Cho, R. Lucka, P.J. Maga, Modeling of reciprocating internal combustion engines for power generation and heat recovery, Appl. Energy 102 (2013) 327–335.
[12] J. Lamine, A. Dicks, Fuel Cell Systems Explained, John Wiley & Songs, Ltd, 2001.
[13] S. Qu, X. Li, M. Hou, Z. Shao, B. Yi, The effect of air stoichiometry change on the dynamic behavior of a proton exchange membrane fuel cell, Appl. Energy 185 (2008) 303–310.
[14] M. Kanoglu, Y.A. Çengel, I. Dincer, Efficiency Evaluation of Energy Systems, Springer, 2012.
[15] L.A.H. Nogueira, J.L. Silveira, J.A.P. Balestieri, Exergetic analysis of unit 1 of thermoelectric Piratininga, Technical report GPTII, in: Proceedings of the 10th National Seminar of Production and Transmission of Electric Energy e SNPTEE, Br. Eletrobras/Cigre, Curitiba, 1989, pp. 1–6.
[16] J.L. Silveira, E.M. Leal, L.F.R. Junior, Analysis of a molten carbonate fuel cell: cogeneration to produce electricity and cold water, Energy 26 (2001) 891–904.
[17] N.A. Madlool, R. Saidur, N.A. Rahim, M.R. Islam, M.S. Hossian, An exergy analysis for cement industries: an overview, Renew. Sustain. Energy Rev. 16 (2012) 921–932.
[18] M.E. Silva, Experimental Analysis of Ethanol Steam Reforming: Technical, Economical and Ecological Aspects (Ph.D thesis), Sao Paulo State University, Guaratinguetá, 2010 (in Portuguese).
[19] D. Bezmalinović, F. Barbir, I. Tolj, Techno-economic analysis of PEM fuel cells role in photovoltaic-based systems for the remote base stations, Int. J. Hydrogen Energy 38 (2013) 417–425.
[20] M.S. Ismail, M. Moghavvemi, T.M.I. Mahlia, Techno-economic analysis of an optimized photovoltaic and diesel generator hybrid power system for remote houses in a tropical climate, Energy Convers. Manag. 69 (2013) 163–173.
[21] S.M. Shaahid, M.A. Elhadidy, Economic analysis of hybrid photovoltaic–diesel–battery power systems for residential loads in hot regions—A step to clean future, Renew. Sustain. Energy Rev. 12 (2008) 488–503.
[22] N. Agarwal, A. Kumar, Varun, Optimization of grid independent hybrid PV–diesel–battery system for power generation in remote villages of Uttar Pradesh, India, Energy Sustain. Dev. 17 (2013) 210–219.
[23] L.B. Braga, Economic Analysis of Fuel Cell in Urban Buses (Masters degree dissertation in mechanical engineering), Energy Department, São Paulo State University, 2010 (in Portuguese).
[24] C.F. Taylor, The Internal-combustion Engine in Theory and Practice: Combustion, Fuels, Materials, Designed, MIT, 1985, ISBN 02627-00271, p. 795.
[25] E.E.S. Lora, M.A.R. Nascimento, Thermal Generation-planning, Design and Operation, Interciencia, Rio de Janeiro, RJ, 2004 (in Portuguese).
[26] L.A.H. Nogueira, E.E.S. Lora, Dendroenergy: Fundamentals and Applications, second ed., Interciencia, Rio de Janeiro, RJ, 2003 (in Portuguese).
[27] I.A.C. Villela, J.L. Silveira, Ecological efficiency in thermoelectric power plants, Appl. Therm. Eng. 27 (2007) 840–847.
[28] Union of Sugarcane Industry from Sao Paulo – ÚNICA, 2010. http://www.unica.com.br.
[29] M. Ball, M. Wietschel, The Hydrogen Economy: Opportunities and Challenges, Cambridge University Press, 2009.
[30] A. Kazim, A novel approach on the determination of the minimal operating efficiency of a PEM fuel cell, Renew. Energy 26 (2002) 479–488.
[31] I. Dincer, M.A. Rosen, EXERGY: Energy, Environment and Sustainable Development, Elsevier, 2007.
[32] Y. Hou, B. Wang, Z. Yang, A method for evaluating the efficiency of PEM fuel cell engine, Appl. Energy 88 (2011) 1181–1186.
[33] H. Wansbrough, Energy: A Refining Crude Oil. v2, The New Zealand Refining Company Ltd, 2011.